Comparative Analysis of Two Compact and Highly Efficient Resonant Switched Capacitor Converters

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Abstract—In this paper we compare two resonant switched capacitor converters in which the resonant inductor can be placed in series with a resonant capacitor (AC side), conducting a sinusoidal current, or it can be placed in series with the input source (DC side), conducting rectified sinusoidal current. Both resonant converters have the same voltage gain, and although the change in the position of the resonant inductor is, at first glance, of minor importance, the analysis and results show that it has huge impact on the capability to achieve ZVS transitions at low output power and on the inductor design and power losses. The experimental results show that for circuit with the resonant inductor in the AC side, the ZVS transitions produce an effective switching frequency significantly higher than the resonant frequency which forces the implementation of cycle skipping at light loads. The difference between the power losses in these two approaches is between 3W and 5W. The prototype implemented for the experiments provides up to 4.5kW with 33.3W power loss (99.3% efficiency). In the case of light load (1.5kW) power losses are only 8.25W ($\eta=99.45\%$). Its power density is higher than 65kW/dm³.

Keywords—Resonant converters, switched capacitors, zero voltage switching

I. INTRODUCTION

Power conversion systems can generally be grouped into single-stage architectures and multi-stage architectures. Although the multi-stage architectures are usually costly and more complex they are used in the cases when the single-stage approach cannot achieve high performance while meeting requirements such as wide operating range, high power density and efficiency. In a multi-stage approach each part of the system is optimally designed to address one part of the desired requirements. Recently, this approach has been applied to achieve highly compact and dense solutions, decreasing the size of the passive components [1-3]. What is common in the recently presented works, it is that the first stage is based on a switched capacitor converter which provides multiple voltage levels in an efficient way. Using multilevel converters the size and power losses of magnetic components, inductors and transformers, the most bulky components, in dc-dc converters, are decreased.

Switched capacitor converters (SCC) have been used as a simple and low cost dc-dc converter in low power applications, [4-6]. These converters normally operate with fixed voltage gains, but with extremely high efficiency. Additionally, due to the lack of magnetic components, they occupy very small

volume obtaining ultra-high power densities. Nevertheless, one of the important issues of these converters are the switching losses, especially if the load power reaches kW levels. In order to avoid high switching losses, a resonant inductor is combined with the “flying” capacitor, producing a resonance and, by correct timing of the transistor control signals, it is possible to obtain soft-switching transitions, Zero Voltage Switching (ZVS). As a consequence, the Resonant Switched Capacitor Converter (RSCC) extends the power range of SCC to high-power applications [7-10]. The resonant inductor is smaller than the inductor employed in classical PWM converters because it does not have to store the energy, just produce the resonance. A voltage divider based on a switching capacitor is a very well-known solution [11-12] and in this paper two resonant switching capacitor converters based on the voltage divider are compared. Figures 1 and 2 show simplified schematics of solutions in which the resonant inductor can be placed in series with the resonant capacitor conducting a sinusoidal current or it can be placed in the DC path of the current, conducting the rectified sinusoidal current. Both resonant converters have the same voltage gain, and although the change in the position of the resonant inductor is, at first glance, of minor importance, the analysis and results show that it has huge impact on the capability to achieve ZVS transitions at low output power and on the inductor design and power losses. The analyzed converters were designed for input voltage between 300V and 500V, providing up to 4.5kW of output power. This fixed gain power converter can be used in applications such as PV boost converter where a high voltage gain and high efficiency in combination with low specific weight is needed.

Fig. 1. Resonant Switched Capacitor Converter – with AC resonant inductor

Fig. 2. Resonant Switched Capacitor Converter – with DC resonant inductor

Hybrid converters using this resonant switched capacitor converter in high power application are previously presented and explained in [13-14], while the analyzed RSCC is presented in [15] as a part of a hybrid boost rectifier.

II. OPERATING PRINCIPLE OF THE RESONANT SWITCHED CAPACITOR CONVERTER

Simplified schematic of the resonant switched capacitor converter with the most important waveforms is shown in Figures 1 and 2. In the case when the resonant inductor is placed in series with the resonant capacitor, its current is purely sinusoidal due to the resonance and due to the fact that the average value of the capacitor current has to be zero. This case we will denominate as a converter with AC resonant inductor. The duty cycle of the converter is, approximately, 50%. During the first half of the switching cycle the resonant network is connected to capacitor C_2 and the load current completely flows through C_1 . During this period of time the resonant capacitor is charged from the input source. In the second half of the switching cycle, the resonant network is connected in parallel to C_1 and its role is to compensate the charge taken from C_1 in the first half of the switching period and to provide the load current. Therefore, we can write the following equations for the C_1 current:

$$i_{C1} = I_o \quad t \in [0, \frac{T}{2}] \quad (1)$$

$$i_{C1} = I_o - I_R \sin(\omega t) \quad t \in [\frac{T}{2}, T] \quad (2)$$

where I_o is the load current, and I_R the amplitude of the resonant current. As the net charge of this capacitor must be equal to zero over one switching period by averaging its current it is obtained that:

$$I_R = \pi I_o \quad (3)$$

If we analyze the current I_{rect} that flows between the middle point of C_1 and C_2 and the middle point of Q_2 and Q_3 we can conclude that this current has the waveform of the rectified resonant current. Therefore, if we place the resonant inductor between these points, the resonance will be maintained and the circuit will provide output voltage two times higher than the input just like in the previous case. This case we will denominate as a converter with DC resonant inductor. Although there is no difference how these two circuits operate, the inductor displacement produces two important changes.

The first one is obvious and it is related with the current through the resonant inductor. The rectified sine wave current has major part of its spectrum in the DC part, therefore, it is possible to exploit low DC resistance of the windings and decrease the power losses in the windings. Nevertheless, the core losses are influenced by the frequency and amplitude of the magnetic flux change. The excursion of the magnetic flux is just one half in comparison with the original design, but double the resonant frequency. This might provoke higher core losses in the design. The second important change is regarding the control signals sent to the switches in order to obtain the ZVS transitions, like it is shown in Figures 3 and 4. During this transition two transistors must be turned off and two transistors turned on. In case of both analyzed converters the ZVS transition starts when one conducting transistor is turned off. It has to be turned off with sufficiently high current level, I_{open} , in order to have enough energy in the resonant inductor to accomplish soft transition. The first ZVS transition occurs between t_1 and t_4 in Figures 3 and 4. During this time the resonant current interacts with transistor's C_{oss} capacitances. In this paper the analyzed converter can operate up to 1000V and for this reason the employed devices are Si CoolMOS transistors that exhibit highly nonlinear C_{oss} . This capacitance could be modelled with a piecewise linear characteristic and roughly approximated with only two values. Due to this nonlinearity, the resonant current does not have a linear shape between t_1 and t_2 . Figure 5 shows more details regarding this transition.

Ideally, the resonant current and voltage across C_{oss} reach zero at t_2 . Nevertheless, in order to have both conditions fulfilled, the energy in the resonant inductor at t_1 has to be considerably high, especially if there are several transistors in parallel per switch. This can be obtained or by increasing the level of the resonant current in the moment when the ZVS transition is started or by increasing the value of the inductor. The first approach leads to higher turn off losses, while the second one to an unacceptably bulky inductor. Therefore, a trade-off must be made by performing a “partial ZVS”, i.e. the switch is closed when the voltage across C_{oss} reaches 20V-40V, [16]. In another words, at t_2 only the resonant current will reach zero.

During very short period of time, from t_2 to t_3 there will be two transistors conducting in both converters and actually this time period can be skipped, although inherently will exist due to driver delays during very short moment. The second ZVS transition occurs from t_3 to t_4 . During this time period the resonant current is becoming more negative and the energy of the resonant inductor is rising. Therefore, during this time period it is possible to obtain full ZVS, fully discharging C_{oss} of the turned off transistor. Until t_4 the resonant current behaves in the same way in both analyzed converters and in both cases it will approximately reach value of

$$I_{neg} = -\sqrt{\frac{2V_{in}V_oC_oN}{L}} \quad (4)$$

Fig 3 ZVS transition in the case of the Resonant Switched Capacitor Converter with an AC resonant inductor

Fig 4 ZVS transition in the case of the Resonant Switched Capacitor Converter with a DC resonant inductor

Fig. 5. Partial ZVS transition from t_1 to t_2

where N is the number of the transistors in parallel, L the value of the resonant inductor and the C_{oss} is modelled as:

$$C_{oss} = \begin{cases} C_0, & V_{ds} < V_0 \\ 0 & V_{ds} > V_0 \end{cases} \quad (5)$$

After t_4 , the resonant current is negative and in the case of the converter with AC resonant inductor it will decrease, while in the case of the converter with DC resonant inductor it will start increasing. This is the key difference between the analyzed converters as it has a major impact on the switching frequency. The difference in the switching frequency comes from a fact that in the case of the DC resonant inductor the resonant current has to change its sign, reach value of $I_{R1} \approx \pi I_0$ and then fall to I_{open} . This lasts very close to a half of the resonant period. On the other hand, with the AC resonant inductor, the resonant current decreases to $-I_{R2} \approx -\pi I_0$ and then rises to $-I_{open}$, as shown in Figure 3. In this case the switching period is obviously shorter than the resonance and it will depend on the value of the load current, i.e. the difference between the $-I_R$ and I_{min} . This difference is shorter as the load current is decreased and in some extreme cases when I_{min} decreases to $-I_R$ the switching frequency can be almost double the resonant frequency of the converter. This means that in the case of the converter with AC resonant inductor the switching frequency will be load dependent and that the lower the load the higher the switching frequency which leads to high switching losses at light load which is exactly what should be avoided.

III. DESIGN, ANALYSIS AND COMPARISON OF RESONANT CONVERTERS

Both converters were designed by exploring the very limits from the point of view of the converter's efficiency and size. The design has been performed by modelling inductor and semiconductor losses and obtaining the Pareto front of the both designs. The electrical specifications are presented in Table 1 and obtained Pareto front in Figure 6. The Pareto front is obtained for the nominal conditions, but each design can survive the worst case. As it can be seen, there are significantly less solutions for the converter design with the AC resonant inductor. The minimum power losses in this case are around 6.5W and the minimum volume around 50cm³. The fact that the resonant current is a sine wave influences the conduction losses so much that the power losses in the case of the DC resonant inductor can be up to 2W less. Additionally, for low volume designs it is necessary to use a small inductance and in the case of the AC resonant inductor where the switching frequency is load dependent this leads to undesirably high switching losses and limits the minimum volume. The theoretical analysis has shown that by changing the position of the resonant inductor it is possible to decrease the volume of the RSCC by 30% while the power losses could be, almost, halved for the same converter volume. However, the most important conclusion is that using the DC resonant converter it is possible to find solutions that are more efficient and smaller than any other RSCC implemented with an AC resonant inductor.

For the prototype design designs that have power losses up to 6W and volumes less than 55cm³ were selected as possible candidates. After more detailed thermal analysis of the resonant inductor the design from Table 2 was selected. As it can be seen the final resonant inductor was implemented with MPP magnetic material as it showed better results than the ferrite inductor of identical volume from the point of view of core losses. The resonant inductor implemented with MPP material will have decreased inductance at high current levels, which will produce a resonant response that will not be purely sinusoidal, but this does not cause any problem as it will be shown later in experiments. For the bus capacitors, C₁ and C₂, Ceralink capacitors were selected due to their high power density. On the other hand, the resonant capacitor was implemented with a Multilayer Ceramic Capacitor (MCC). Different dielectrics such as C0G, X6S or X7T could be selected. Nevertheless, after a series of experiments in which the resonant capacitor was stressed and the temperature rise was observed [17] X7T was chosen. It is interesting to notice that film based capacitors would provide better converter robustness as their temperature rise is significantly lower, but they occupy some more space than X7T MCC, Figure 7.

TABLE I: ELECTRICAL SPECIFICATIONS OF THE ANALYZED RESONANT CONVERTER

Input voltage range	350V-500V
Maximum output power	4.5kW
Nominal input voltage	580V
Nominal output power	1.5kW

Fig. 6. Pareto front of the analyzed Resonant Switched Capacitor Converters

TABLE II: DESIGN DETAILS OF THE IMPLEMENTED RESONANT SWITCHED CAPACITOR CONVERTER

Component	Volume
Bus capacitors Ceralink 20uF	8.2 cm ³
Resonant Capacitors MLCC X7R 5uF	2 cm ³
55uH Resonant Inductance MPP 55071	28 cm ³
Transistors 2 MOSFETS per switch	7.2 cm ³
Total	45.4 cm³

Fig. 7 Temperature rise of the resonant capacitors in the case of different capacitor technologies

Fig. 8 Implemented Resonant Switched Capacitor Converter

The implemented prototype is capable of processing 4.5kW, as demanded by the specifications, and its power density is higher than 65kW/dm³. The predicted power losses were around 6W due to relatively high I_{open} current needed for the ZVS (between 4A and 6A). Figure 8 shows a photograph of the implemented converter.

Comparing it with the case when the resonant inductor is in series with the resonant capacitor, the DC resonant inductor handles only one half of the excursion of the magnetic field, but at the double frequency. As the β factor in the Steinmetz equation is, approximately, between 2 and 2.5 for the materials of interest, the core losses will be in the worst case equal in both resonant converters as the α factor should be higher than 2 to have higher cores losses in the case of the DC resonant inductor. Speaking about the losses in the conductors, DC resonant inductor has a major part of the current in the DC part of the spectrum and, therefore, the conduction losses will be smaller. However, the biggest advantage of the RSCC with DC resonant inductor is that it can correctly operate even without load. To keep the voltage of the bus capacitors balanced, RSCC has to operate even without load. When the DC resonant inductor is applied, it does not need any special modulation, like cycle skipping, to operate correctly fulfilling ZVS conditions and keeping the voltages balanced.

In Figures 9 and 10 can be observed that drain source voltage of switches differ depending on the position of the resonant inductor. In one case the voltage is clamped to the input voltage and in the other case it is the output voltage minus the voltage in the resonant capacitor, which has some ripple.

As it has been explained earlier, the peak of the resonant current decreases when the output power is decreased as shown in Figure 11. In the case of the AC resonant inductor this might be a problem because as the peak of the resonant current falls below the value that is necessary to achieve ZVS could lead to important power losses. Even more, in the case of the analyzed system, in the low power conditions this is what exactly happens and, in order to avoid it, it is necessary to employ cycle skipping. For example, if one resonant cycle is skipped, the peak of the resonant current is doubled and ZVS could be achieved. Figure 12 shows possible cycle skipping strategies and at the same time illustrates the bad side of this approach. In the first strategy, the resonance is started and it is let to naturally end after half the resonant cycle, the pause is made and then the second half of resonant cycle is performed. It can be seen that whenever the current reaches zero there are high frequency oscillations of drain-source voltage (pink trace) due to the resonance between the MOSFET C_{oss} and resonant inductor. This kind of oscillations can be observed in any converter that operates in Discontinuous Conduction Mode.

These oscillations produce power losses which are not present if pulses are not skipped. Also, in order to start the resonance, hard discharge of the MOSFET's C_{oss} occurs and soft turn on is impossible. To decrease the amount of power losses due to these two mechanisms, in the second approach a complete cycle is performed, with one ZVS transition, and then the needed pause is made, Fig. 13. With this strategy the power losses due to hard turn on and due to the parasitic oscillations are decreased to one half. For the analyzed RSCC converter at $1.5\text{kW}@V_{out}=700\text{V}$ the power losses were 14W for the first strategy and 12W in the second case

Fig 11 Comparison of RSCC resonant currents in the case of the nominal and full load – DC resonant inductor design

Fig 12 Half cycle resonance Resonant current (blue), resonant capacitor voltage (red) and MOSFET V_{ds} (green and pink) in the case of resonant inductor at AC side and nominal output power

Fig 13 One cycle resonance Resonant current (yellow) and MOSFET V_{ds} (blue and pink) in the case of resonant inductor at AC side and nominal output power

In the case of the RSCC with DC resonant inductor the ZVS condition is easier to accomplish as it is shown in Figure 11. In this figure resonant current at nominal and full load are compared. The negative current is needed for the ZVS and it helps increasing the peak of the resonant current (in order to maintain the needed DC level of the input current). Even when the RSCC is without load, the current will resonate and the MOSFET transitions are partially soft, Figure 14. In the case when the output power from the RSCC is 0W, the measured power losses are less than 5W. At full load ($4.4\text{kW}@V_{out}=700\text{V}$) the measured power losses were 33.3W, Figure 15, while at nominal load ($1.5\text{kW}@V_{out}=700\text{V}$) the measured power losses are 8.25W (50% lower than in the case of AC resonant inductor with cycle skipping), Fig 16. The measured power loss is around 2W higher than the calculated one and further work must be performed to analyze the difference between the theoretical and measured efficiency.

Fig 14 Resonant current (blue trace) and drain-source voltages (red and green traces) when RSCC operates without load - case of DC resonant inductor

Fig 15 Resonant current, drain-source voltage and inductor temperature when the resonant converter operates in its worst case (output power of 4.4kW)

Fig 16 Resonant current, drain-source voltage and inductor temperature when the resonant converter processes its nominal power of 1.5kW

V. CONCLUSIONS

Multi-stage converters that include a Resonant Switched Capacitor Converter (RSCC) are normally employed in the solutions that require high efficiency and power density. The RSCC can be implemented with the resonant inductor in series with the resonant capacitor (AC inductor approach) or with the resonant inductor in series with the input source (DC inductor approach). The main difference between these two implementations is the shape and frequency of the resonant current. In the case of the AC resonant inductor, the shape and frequency of the current are load dependent. It is a sine wave, for heavy loads, while in the case of light loads, the current has, practically, trapezoidal waveform. In the case of the DC resonant inductor, the current is a rectified sine wave almost for all loads. This difference in the current waveforms is of the utmost importance and the RSCC with DC resonant inductor can achieve 50% less power losses and designs that occupy 40% less volume. Due to the load dependent resonant current the RSCC with AC resonant current cannot achieve ZVS even at nominal load and techniques such as cycle skipping has to be applied. Nevertheless, cycle skipping might produce additional power losses due to the parasitic oscillations between the resonant inductance and MOSFET's C_{oss} . On the other hand, RSCC with DC resonant inductor operates without any problem at light load (1.5kW of output power) with only 8.25W of power losses. The achieved power density of the designed RSCC is higher than 65kW/dm³.

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